Reliability Assurance in RIS-assisted 6G Campus Networks

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2024 20th International Conference on the Design of Reliable Communication Networks (DRCN) | 979-8-3503-4897-2/24/$31.00 ©2024 IEEE | DOI: 10.1109/DRCN60692.2024.10539144

***Abstract*—Campus networks have become a major market segment for cellular communication technology, providing a flexible communication infrastructure to meet the specific dependability and performance requirements of industry verticals. With the emerging 6G technologies, an order of magnitude higher throughput is on the horizon, however, the higher communication frequencies are more susceptible to line-of-sight (LOS) blockages. One way to tackle this issue is a dense installation of base stations (BSs). However, as a more cost-efficient alternative, this paper explores how to assure the reliability of communication links in such scenarios, by analyzing the efficacy of Reconfigurable Intelligent Surface (RIS). We present a model and optimization framework to efficiently maintain connectivity in a factory environment case study. Our model also takes into account the realistic assumptions imposed by the limitations of RIS technology and the practical constraints of campus networks. We address the resource allocation problem, proposing two approaches namely, an Integer Linear Programming (ILP) and a heuristic method. Our results showcase the tangible benefits of RIS in providing continuous connectivity while reducing outages.**

***Index Terms*—Reconfigurable intelligent surface, Campus networks, 6G, Reliability.**

I. Introduction

The demand for higher bandwidth, lower latency, and increased reliability in wireless networks is continuously growing. This trend is particularly evident in the development from 5G to the upcoming 6G, where the utilization of higher frequencies, such as mmWave and sub-THz channels, is becoming increasingly extended [1]. While these higher frequencies offer enhanced bandwidth and reduced latency, they also present challenges related to reliability, primarily due to the requirement for a direct line of sight between the sender and receiver [2]. Any obstruction, whether a physical structure or even human movement, can significantly degrade the communication channel [3]. In response to these challenges, traditional mobile network deployments, typically characterized by cell towers, must adapt to support these higher frequencies effectively. One potential adaptation involves the integration of RISs into the network infrastructure [4]–[7]. Like mirrors for visible light, RIS enables the reflection of radio waves, effectively extending coverage to areas that lack a direct line of sight to an antenna or base station due to obstructions [8]. Furthermore, RIS can be dynamically reconfigured to selectively reflect specific frequencies, catering to the needs of specific users at any given time. While extensive research has been conducted on RIS's engineering and physical aspects, limited attention has been given to their integration into existing radio access network architectures. Integrating RIS into existing network architectures necessitates considerations distinct from those associated with traditional radio units (RUs) or BSs. Factors such as the assignment of RIS to user equipment (UE), the management of handovers between RUs and RIS (termed restoration handovers), and the reconfiguration time of RIS are critical areas of focus [9], [10]. The reconfiguration time of RIS, influenced by variables such as the angle of reflection and the material composition, is a significant consideration, with current research indicating times in the order of hundreds of milliseconds [11], [12].

One specific area of interest is the potential application of 6G and RIS in private campus networks [13]. Unlike public mobile networks, private campus networks offer use cases where substantial information about user behavior is available in advance. In this context, we aim to analyze how RIS can support specific use cases, such as in a factory floor scenario where the movement paths of robots are predetermined. In this scenario, RIS strategically placed around the factory can compensate for areas blocked by physical objects, optimizing network coverage. Given the pre-known positions of all robots, the objective is to develop a scheduling mechanism that optimally assigns RIS to robots, considering the reconfiguration time, to minimize the duration during which robots experience connectivity issues due to line-of-sight blockages [14].

In this paper, we first formulate this scenario as an optimization problem. We then simulate robots moving around a predetermined topology with various RIS and a fixed BS. We consider both cases of robots moving along random paths and manually created paths. From the results of these simulations, we are using both an ILP and a benchmark heuristic to assign RIS to robots. We do this while varying several different factors, such as the number of robots, the time robots can keep moving without coverage and the time it takes a RIS to switch from one robot to the next. Finally, we compare the results of the ILP and heuristic against each other and against

The authors acknowledge the financial support by the Federal Ministry of Education and Research of Germany in the programme of "Souverän. Digital. Vernetzt." Joint project 6G-RIC, project identification number: 16KISK020K, 16KISK030 and 16KISK031, and partial support by the DFG Project Nr. JU2757/12-1.

the case of not having any RIS present.

A. Literature review

There are several different areas of relevant related work. First, there have been studies that analyze the benefit of adding RIS to a network. The potential benefits of using RISs in various wireless communication setups, including indoor and outdoor environments, and across different frequency bands, are investigated in [15]. The authors first studied the impact of the number of reflecting elements on a single RIS on performance metrics such as received signal-to-noise ratio (SNR) and error performance. Then, they developed transmission models for multiple RISs and analyzed them for both indoor and outdoor non-line-of-sight (NLOS) scenarios. They also integrated conventional RIS selection strategies for multi-RIS systems. The results indicate that RISs can provide significant performance improvements in error performance and achievable data rates, even under imperfect channel conditions. Similarly, in [16], a MEC (Mobile Edge Computing)-enabled and RIS-assisted THz virtual reality network is proposed. The network achieves near-optimal quality of experience (QoE) in indoor scenarios with two times improvement in QoE compared to random phase shift selection (RPSS) schemes.

In [17], Blind-RIS-NOMA improves spectrum efficiency and connectivity in 5G networks by regulating radio propagation environments, enhancing sum capacity and outage performances by 38% compared to conventional NOMA. A RIS-aided multiple-input-single-output (MISO) communication system in [18] using rate-splitting multiple access (RSMA) protocol can effectively reduce outage probability and improve performance. In [19], multi-RIS systems with bounded backhaul capacity can achieve minimal outage and rate maximization but require backhaul capacity to ensure performance gains compared to single-RIS systems. While these all establish the benefit RIS can theoretically have on various wireless environments, the applications they showcase are mostly specific.

Comparatively, our work will provide a general-purpose analysis and simulation of the efficiency gains by adding RIS to a wireless scenario. With the general utility of RIS established, there is also a need to consider how to integrate them into existing mobile networks, particularly from a control and routing perspective. Mechanisms to deal with this problem have been proposed and studied in several publications [20] [21]. In particular, handover schemes using RIS and deep reinforcement learning [22] and routing [23], [24]. Finally, optimization problems involving RIS have also been the topic of research, though they focused on data rates and reliability in specific environments such as wireless virtual reality networks [25]. In comparison to this, our investigation focuses on the optimization of assigning RIS to UEs.

B. Contributions

We initiate the study of how to enhance the reliability of communication in campus networks using RIS. Our model incorporates realistic factors, including the reconfiguration time for RIS, and introduces an optimization framework designed to minimize robot outage time within the campus. This framework considers constraints dictated by Quality-of-Service (QoS) requirements, such as the maximum allowable consecutive outage time. By exploring the benefits of RIS enhancement in the network, we aim to understand the inherent tradeoff among different parameters. To address the resource allocation problem, we propose two approaches. Our simulations demonstrate a substantial reduction in outage time and an improvement in meeting the required QoS standards within a campus network.

The paper's contributions are outlined as follows:

- Enhanced the system model to incorporate realistic elements, including reconfiguration time. This time, beyond hardware considerations, accounts for the delay associated with control plane actions needed to reallocate a RIS from one robot to another.
- Introduced outage time as a metric for connection reliability, along with defining a maximum allowed consecutive outage to meet QoS requirements.
- Formulated the resource allocation problem, employing linearization techniques to establish a linear optimization problem.
- Highlighted the inherent tradeoff arising from the control overhead introduced by integrating RIS and rerouting.
- Utilized numerical simulations to showcase the advantages of RIS in ensuring reliability as a cost-effective technology and examined the impact of various parameters on performance.

II. System Model

Consider the wireless campus network depicted in Fig. 1, which comprises a BS, I RISs, and R robots moving within a factory setting. Existing blockages within the factory, such as walls and shelves, can obstruct the LOS path between the BS and the robots. As shown in Fig. 1, since the robots are mobile, these LOS blockages can change over time. Due to the higher frequency assumption, i.e., mmWave communication, maintaining a clear LOS link is essential for ensuring a reliable connection. Therefore, the network operator installs RISs to extend the coverage provided directly by the BS, creating what is known as the virtual LOS (vLOS) [26]. This ensures that connections between the BS and robots are always maintained.

In the following, we introduce different components of the system model and define the considered assumptions in several subsections.

A. Scenario

We discretize the time interval of interest $[0, T]$, into N time slots, T_1 through T_N, each with a duration of ΔT, such that $T = N\Delta T$.

In the considered context of campus networks and particularly for the high-frequency assumption, the channels are assumed to be deterministic and priorly known in advance for every location. For instance, the existence of an LOS path or a blocked LOS is known. This implicitly means the entire environment, apart from the robots, is static during the time interval of interest, i.e., there are no other moving objects.

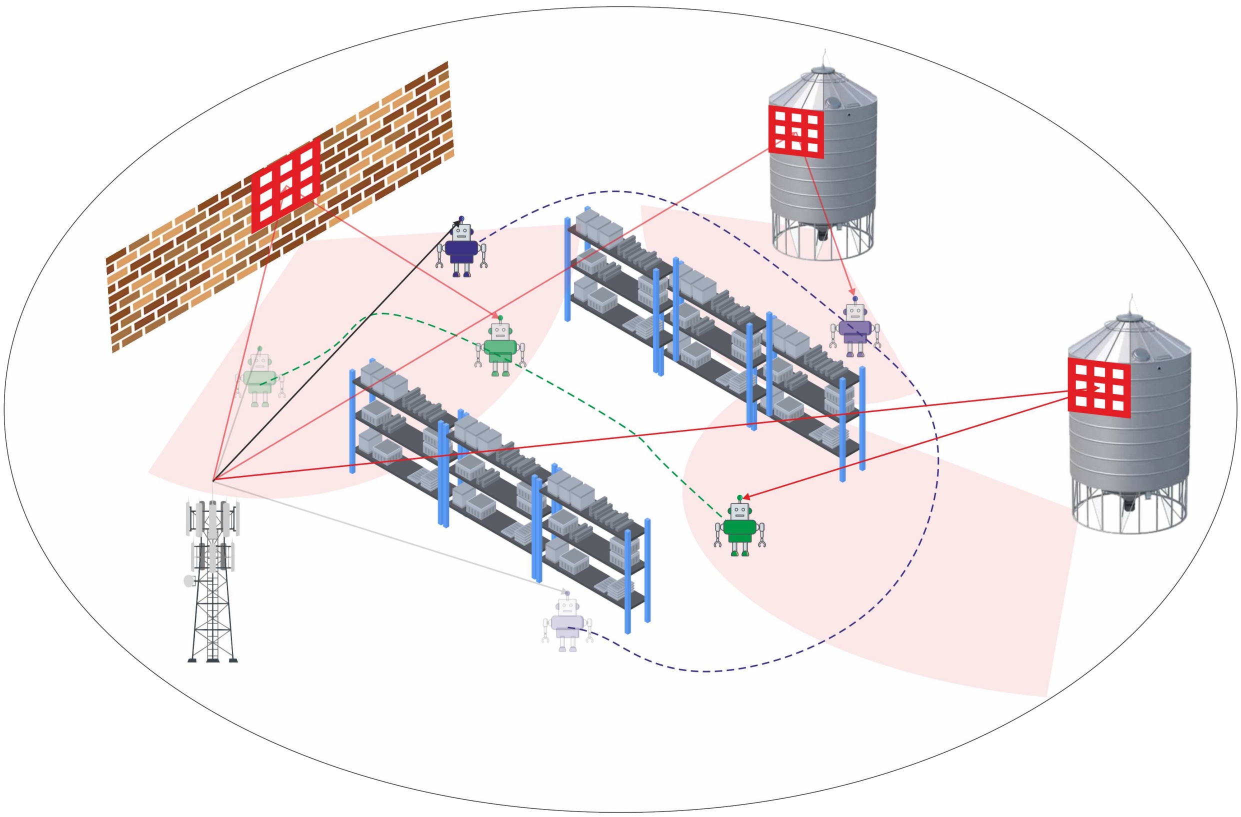


Fig. 1: An illustration of a RIS-assisted campus network. Two robots (in green and blue) move within the factory with certain trajectories. RISs are depicted in red with a highlighted red surface in front demonstrating the coverage area.

Moreover, we adopt a binary model for the channel quality, only differentiating between the robot being in the coverage area or not, i.e., whether there exists an LOS link and it is within the range.

The BS is located at $\mathbf{P}^B$ and RISs are located at $\mathbf{P}_i^I, i = 1, \cdots, I$. RISs are assumed to be deployed in locations/orientations that have LOS paths to the BS. Moreover, given the location and orientation of each RIS, the region of coverage for a RIS is predefined. In other words, it is known in advance, if a specific RIS can cover a robot in a certain location. Ultimately, it is known for each time step, which robot is in the coverage area of which RIS/BS.

To formalize this notion, denoting the whole area of interest, i.e., are of the campus, by $\mathcal{F}$, we denote the coverage area via RIS i by $\mathcal{F}_i \subseteq \mathcal{F}$. Moreover, the coverage area by the BS is denoted by $\mathcal{F}_B$.

B. Robots

Robots are assumed to have omnidirectional antennas to communicate with the BS, i.e., there is no beamforming at the robot. Moreover, the path that a robot is taking is known. Therefore, in principle, it is clear at what period of time, there is no LOS connection between robot r and BS, and possibly what RIS can provide a vLOS link for that location.

The location of robot r at time slot T_n is denoted by $\mathbf{L}_{r,n}$. As soon as a robot is covered neither by the BS nor RISs, the robot is considered to be in an outage. Based on the speed of the robots as well as the service that they are providing, the maximum allowed time of consecutive outage for robots is defined, which is denoted by T_{th}, i.e., It is a failure if the outage continues for a time longer than T_{th}.

C. RIS Configuration

In this paper, we consider RIS with ideal hardware implementation, therefore, hardware impairments are neglected. RISs are equipped with a predesigned codebook that contains different codewords (i.e., beams) to serve the robots within the coverage area of that specific RIS. The process of reconfiguring a RIS from covering one robot to another is assumed to take $T_{\text{config}} = D\Delta T$ time [1]. If a RIS is not in use, it can pre-align and configure itself in advance with a robot so it does not incur the delay of the reconfiguration time. We also assume that each RIS can only serve one robot at a time.

D. RIS Allocation

We denote RIS allocation to robots with the matrix $\mathbf{X} \in \{0,1\}^{I \times R \times N}$ where $X_{i,r,n} = 1$ means that RIS i is allocated to robot r at time slot n, and not allocated otherwise. Since the RISs are assumed to be allocated to a maximum of one robot at a time, we need to have $\forall i, n: \sum_r X_{i,r,n} \leqslant 1$.

To consider the history of allocation of RISs for the last D time slots, we define the dummy matrix $\mathbf{Y} \in \{0,1\}^{I \times R \times N}$ where $Y_{i,r,n} = 1$ means that RIS i is allocated to robot r at

[1]The implicit assumption here is that as long as a RIS is tracking the same robot, considering the beamwidth and speed of the robots, the reconfiguration is happening smoothly, i.e., with no delay.

least once during the time slots of $[n-D+1, n]$ which is calculated as follows:

$$Y_{i,r,n} = (\sum_{\bar{n}=n-D+1}^{n} X_{i,r,\bar{n}}) \geqslant 1. \tag{1}$$

Moreover, in order to take the required time of reconfiguration into account, we define the change matrix $\mathbf{C} \in \{0,1\}^{I \times N}$ where $C_{i,n} = 1$ means that the RIS i has been reallocated (i.e., reconfigured) in the last D time slots, therefore, it is still not ready. According to the definition of $\mathbf{Y}$, $C_{i,n}$ is one, if $Y_{i,r,n}$ is one for at least two different rs, mathematically

$$\sum_r Y_{i,r,n} - 1 \leqslant C_{i,n}. \tag{2}$$

E. Connection Outage

The connection status of robots is denoted by the matrix $\mathbf{O} \in \{0,1\}^{R \times N}$ where $O_{r,n} = 1$ means an outage for robot r at time n and connection otherwise. If the time without connectivity of a robot, defined as an outage, exceeds the given threshold $T_{\text{th}} = K\Delta T$, it is considered a failure in service. Consequently, the summation of the outage variable of each robot for K consecutive time slots should be always less than K. In cases where an assignment leads to a service failure, the assignment is deemed invalid.

III. Problem Formulation

As mentioned earlier, since the robots are moving within the factory, their channel status varies between LOS and NLOS to the BS. The problem is how to perform resource allocation, i.e., configure/beamform at the RISs, in order to minimize the summation of the outage time of robots, i.e., $\sum_{r=1}^{R}\sum_{n=1}^{N} O_{r,n}$. The optimization problem can be formulated in the following form:

$$\min_{\mathbf{W},\mathbf{X},\mathbf{O},\mathbf{Y},\mathbf{C}} \sum_{r=1}^{R}\sum_{n=1}^{N} O_{r,n} \tag{3a}$$

$$\text{s.t. } \mathbf{X},\mathbf{Y} \in \{0,1\}^{I\times R\times N}, \mathbf{C} \in \{0,1\}^{I\times N}, \mathbf{O} \in \{0,1\}^{R\times N}, \tag{3b}$$

$$\sum_r X_{i,r,n} \leqslant 1, \quad \forall i,n, \tag{3c}$$

$$Y_{i,r,n} = u(\sum_{\bar{n}=\max\{n-D+1,0\}}^{n} X_{i,r,\bar{n}}), \quad \forall i,r,n, \tag{3d}$$

$$C_{i,n} = u(\sum_r Y_{i,r,n} - 1), \quad \forall i,n, \tag{3e}$$

$$\sum_{\bar{n}=n-K+1}^{n} O_{r,\bar{n}} < K, \quad \forall r,n, \tag{3f}$$

$$1 \leqslant [O_{r,n}] + [\sum_{i=1}^{I} X_{i,r,n}(1-C_{i,n})(L_{r,n} \in \mathcal{F}_i)] + [(L_{r,n} \in \mathcal{F}_B)], \quad \forall r,n, \tag{3g}$$

where the objective is to minimize the summation of the outage time of robots, (3b) defines the domain and dimension of the variables, (3c) enforces to allocate each RIS to maximum one robot at a time, for each time slot n, (3d) determines if the RIS i has been allocated to robot r in the last D time slots with $u(\cdot)$ being a step function defined in the following:

$$u(x) = \begin{cases} 0, & \text{if } x < 1, \\ 1, & \text{otherwise.} \end{cases} \tag{4}$$

Moreover, (3e) determines if there has been a change in the allocation of RIS i in the last D time slots, (3f) is to guarantee that there will not be K outages in a row for any robots, and (3g) enforces that either each robot is covered by one of RISs or BS, or calls that time slot an outage for that robot.

Besides the integer variables in (3b), the product of variables in (3g) makes the problem nonlinear. In the following, we introduce the variable matrix $\mathbf{W} \in \{0,1\}^{I\times R\times N}$ with $W_{i,r,n} = X_{i,r,n}(1-C_{i,n})$ that accounts for allocation of RIS i to robot r at time slot n as well as availability of RIS i at time slot n (i.e., the reconfiguration has been done at least D time slots earlier). However, here, we still have the product of the two terms in the definition of $\mathbf{W}$. Thus, to avoid the multiplication of variables and consequently nonlinearity of the problem, we set $W_{i,r,n} \leqslant X_{i,r,n}$ and $W_{i,r,n} \leqslant 1 - C_{i,n}$ which states that $W_{i,r,n}$ is 1 if and only if both $X_{i,r,n}$ and $1 - C_{i,n}$ are 1. Also, since the usage of the step function in (3d) and (3e) is with bounded argument, we use the following technique to eliminate the step function from the formulation in order to further simplify the problem. In essence, if the argument of step function x belongs to a range $[0, M]$, $\frac{1}{M}x$ provides a similar (with some extra considerations) result as $u(x)$. Applying all the mentioned techniques, we can reformulate the optimization problem in the following form:

$$\min_{\mathbf{W},\mathbf{X},\mathbf{O},\mathbf{Y},\mathbf{C}} \sum_{r=1}^{R}\sum_{n=1}^{N} O_{r,n} \tag{5a}$$

$$\text{s.t. } (3b), \mathbf{W} \in \{0,1\}^{I\times R\times N}, \tag{5b}$$

$$\sum_r X_{i,r,n} \leqslant 1, \quad \forall i,n, \tag{5c}$$

$$\frac{1}{D}\sum_{\bar{n}=\max\{n-D+1,0\}}^{n} X_{i,r,\bar{n}} \leqslant Y_{i,r,n}, \quad \forall i,r,n, \tag{5d}$$

$$\frac{1}{R}\sum_r Y_{i,r,n} - \frac{1}{R} \leqslant C_{i,n}, \quad \forall i,n, \tag{5e}$$

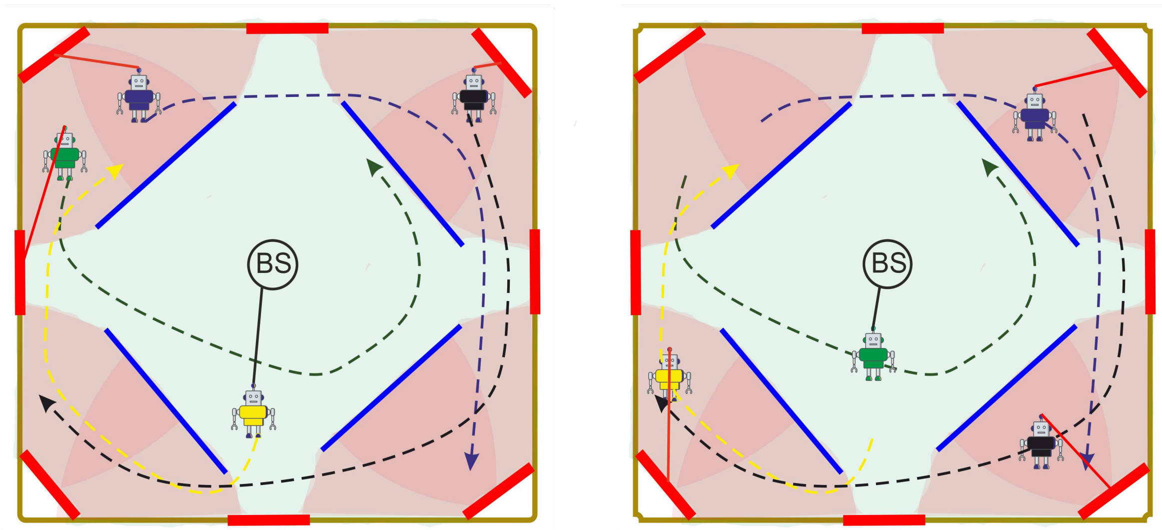
$$\sum_{\bar{n}=\max\{n-K+1,0\}}^{n} O_{r,\bar{n}} < K, \quad \forall r,n, \tag{5f}$$

$$1 \leqslant [O_{r,n}] + [\sum_{i=1}^{I} W_{i,r,n}(L_{r,n} \in \mathcal{F}_i)] + [(L_{r,n} \in \mathcal{F}_B)], \quad \forall r,n, \tag{5g}$$

$$W_{i,r,n} \leqslant X_{i,r,n}, \quad W_{i,r,n} \leqslant 1 - C_{i,n}, \quad \forall i,r,n. \tag{5h}$$

IV. Control Mechanism

There are two main models for RAN architecture: First, there is the so far more common aggregated model where all relevant functions and control are handled by monolithic black boxes that vary from vendor to vendor. Second, the open radio access network (O-RAN) architecture aims to promote disaggregation of network functions and open, standardized interfaces between the individual components. For our proposed



(a) Time slot 1

(b) Time slot 15

Fig. 2: Illustration of BS/RIS connections to robots at two different time slots for a scenario with 8 RISs, 4 robots, and with K = 10 and D = 2 time slots.

control scheme we will focus on the O-RAN architecture. Its current specifications do not include RIS, and as such they will have to eventually be extended to allow for their integration. However, it is not our goal to propose any new standards but merely to give a high-level overview of the challenges and possible mechanisms involved.

In O-RAN-, so-called radio intelligent controllers (RICs) are responsible for managing and controlling the individual elements of the network. It is not clear yet which of these RICs will be the right one for controlling RIS and which interface type will be used to connect them. This will largely depend on latency requirements for the necessary control mechanisms. It is tightly coupled with whether or not a new real-time RIC will be added to support possible new functionality for the sub-THz domain. There have been proposals [27] to this end to reduce the 10 ms timescale the nearRT-RIC offers. However, it is clear that the control will have to be done by the RIC and not i.e. the radio unit (RU) as, unlike in our example, the same RIS might be available to multiple RUs. The RIS itself can also not be used for control as it is entirely, apart from adjusting its configuration to target a specific UE, passive. This is also one of the major differences between RUs and RIS. As RIS is not capable of doing any channel estimation, beamforming, steering, etc., they are entirely reliant on instructions from third parties. These could come in the form of codes from a pre-determined and shared codebook. The RIS would then simply configure itself accordingly. The sharing and updating of the codebook is also a responsibility of the RAN, but this is on a different layer as it is related to management and orchestration as opposed to control. Particular challenges that will require further research and investigation when it comes to RIS control are initial connections to UEs that enter the coverage area of a RIS before having been in the coverage area of an RU. Additionally, beam sweeping and steering will require new considerations on the RU side, as the presence of a RIS on the path might have implications for them.

This paper addresses the aspect of reconfiguration time, denoted as D. This time is influenced not only by hardware factors but also by aspects such as learning, optimization, and control. A key research question emerges: when is it beneficial to employ RIS despite the tradeoff of introducing more complex control? Specifically, rerouting has implications for the delay D, a significant reliability factor. Minimizing rerouting is advantageous (less impact on higher layers), creating a tradeoff between outage reduction and increased rerouting.

V. Simulation Results

We propose two methods to tackle the RIS-robot allocation problem: an ILP and a heuristic method. For the ILP, we employ the *intlinprog* function of Matlab to solve the linear optimization problem formulated in Section III. Furthermore, the proposed heuristic method attempts to connect one of the RISs from the set of possible RISs (i.e., the RISs that cover the current location of the robot) subject to the availability of the RIS (i.e., not connected to another robot) at that time slot. Moreover, if a robot can connect directly to the BS, it will do that with the highest priority.

The RIS configuration time is D time slots, as discussed in II-C. Therefore, at a time slot n, $C_{i,n}$ = 1 means that the RIS i has been reallocated in the last D time slots, i.e., it is still not ready; otherwise, it is ready for a new configuration for a new robot, as discussed in II-D. The consecutive outage time for a robot must always be less than K, as discussed in II-E.

Our simulation consists of a varying number of robots moving around a manually created floor plan that includes a BS and 8 RISs, as shown in Fig. 2. Both the placement and movement of each robot are random. A Python script generated all robots and movements. Each robot moves five steps in the same direction before changing course to make the pattern more realistic. A second Python script was used to generate, for each robot, a list of all coverage areas they are within at any given time slot. This includes both the coverage provided by the RIS as well as the BS. We run 100 random independent scenarios for each case to obtain the average values with confidence intervals of 95%.

A. Toy Example

We begin with a small-scale example illustrating resource allocation over time. In Fig. 2, the scenario is depicted at two different time slots – 1st and 15th. In this toy example with 8 RISs, 4 robots move along their trajectories. The green area represents the coverage of the BS, while the red areas indicate RIS coverage. Notably, there are overlaps between BS and RIS coverage areas (overcolored in green) and between the coverage areas of two RISs (colored in darker red). This overlap provides robots with multiple connection options, such as connecting to a BS and a RIS or two RISs. This flexibility enables the resource allocation algorithm to optimize long-term objectives. For instance, even if a robot is crossing the BS coverage area, if it will soon encounter an LOS blockage, the controller may choose to maintain the connection with the current RIS. The figure illustrates the allocated RIS or BS to each robot at each time slot.

B. RIS-assisted Connectivity Results

Two metrics are considered to assess the proposed algorithms' performance and observe the improvement facilitated by RIS compared to the no-RIS case. The first metric is the percentage of outages, defined as the ratio of the total number of outages over the product of the total number of time slots and the number of robots. Mathematically, it is represented as

$$\frac{\sum_{r=1}^{R}\sum_{n=1}^{N} O_{r,n}}{RN}$$

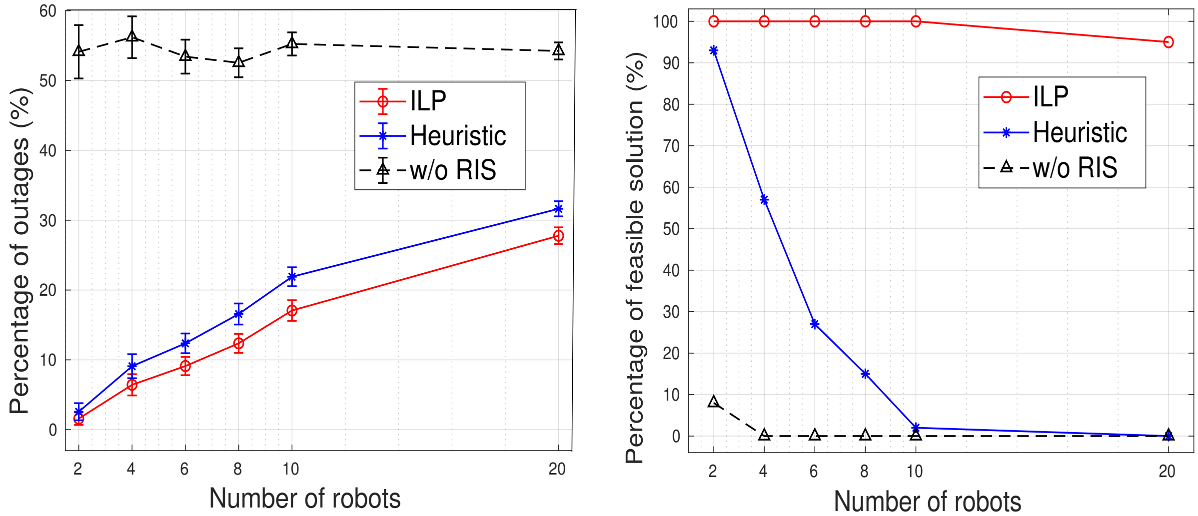
Additionally, given that the problem or scenario may, in some cases, be infeasible or the proposed methods might fail to find a feasible solution, the percentage of feasible solutions is also plotted. This is calculated as the number of feasible scenarios (those with a feasible solution) over the total number of scenarios. Thus, no confidence intervals can be calculated since it is a counting.

Fig. 3 illustrates the performance, specifically the percentage of outages and percentage of feasible solutions, concerning the number of robots. In this scenario, the configuration time is set to $D = 2$ time slots, and the consecutive outage time for a robot must always be less than $K = 10$ time slots. To add a baseline, we also included the results for the same scenario and robot movements without the ability to use the RIS (w/o RIS). As anticipated, with an increasing number of robots the percentage of outages (depicted in Fig. 3(a)) remains more or less constant for the case with no RIS. This is due to the fact, that it is only directly dependent on the number of robots inside the BS coverage area. Since in our scenario, the BS covers around 51.5% of the entire area and the robots placement and movement is random, the results remain close to that value. Meanwhile, it rises for both the ILP and heuristic methods. This is attributed to intensified competition among robots to connect to RISs, while the number of RISs in the system remains fixed at $I = 8$. Although the proposed ILP performs superior to the heuristic method due to its long-term optimization, both exhibit higher percentages than the no-RIS case. This underscores the primary advantage of utilizing a cost-effective solution, such as employing RIS, to enhance reliability. Similarly, the percentage of feasible solutions for the ILP surpasses that of the heuristic method, as depicted in Fig. 3(b). For instance, with a scenario involving $R = 10$ robots, the ILP achieves up to 100% feasibility, whereas the heuristic method achieves only 1%. Additionally, in the scenario with $R = 2$ robots, both methods exhibit similar percentages of outages and feasible solutions due to reduced competition among robots. Finally, the percentage of feasible solutions of both the ILP and heuristic methods is better than that of the no-RIS case. The significantly higher feasibility rates of the ILP showcases the fact that it is not simply enough to place RIS in a scenario but there is also a need to implement appropriate optimizations of their assignment to robots. Otherwise, their usability quickly diminishes with increasing the number of robots.

Since the case with no-RIS is not dependent on D while for K it would only impact the feasible solutions, as robots can venture outside of the BS coverage area for longer before becoming unfeasible, we will from now on only plot the results of ILP and heuristic. This is also done to make the comparison between ILP and heuristic easier in the plots.

Next, we analyze the impact of the reconfiguration delay D on the network performance. The percentage of outages and the percentage of feasible solutions versus D for the result obtained from ILP and the heuristic methods are plotted in Fig. 4. As expected, by increasing D, we are essentially increasing the unavailability period of a RIS after reallocation. This extension primarily leads to a rise in outage time and more infeasible solutions. Moreover, it escalates the cost of reallocating a RIS from one robot to another, introducing a new trade-off where, in certain scenarios and under specific conditions, the RIS controller might opt to retain the allocated RIS for a specific robot, even if temporarily outside the coverage area of that RIS or within the coverage of the BS. Additionally, the ILP consistently outperforms the heuristic method for all values of D. Notably, Fig. 4(b) indicates that for the ILP method, infeasible scenarios begin to emerge from $D = 4$.

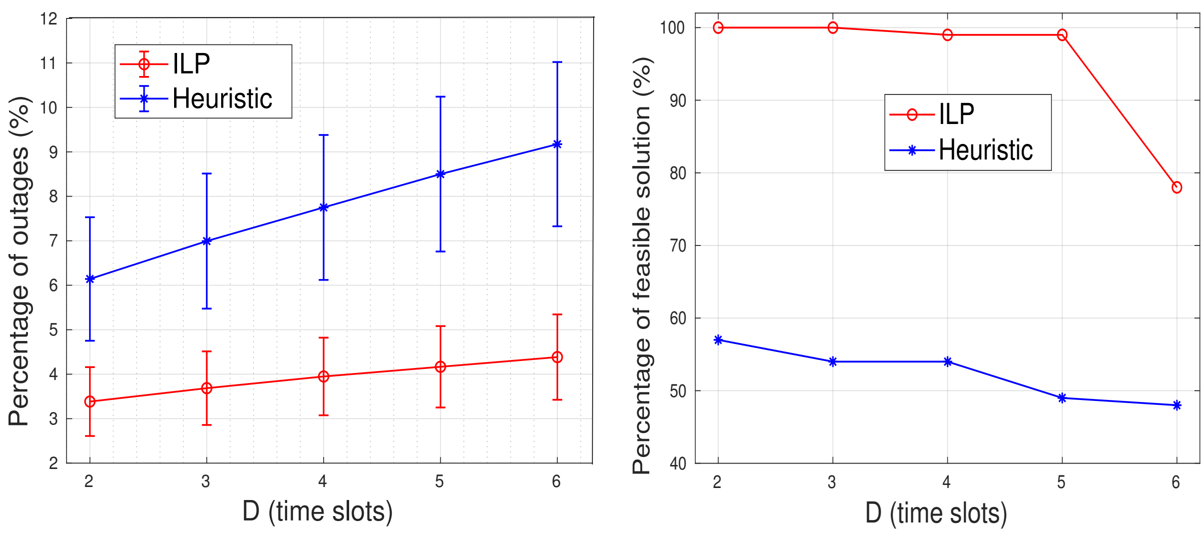
To investigate the impact of the maximum allowed consecutive outages K, imposed by QoS requirements, Fig. 5 displays the performance concerning K. As the heuristic method does not take K into account and consequently does not find feasible solutions in many scenarios, its percentage of outages remains constant with increasing K as shown in Fig. 5(a). However, naturally, as we increase K, we relax the constraint (5f), allowing the ILP to find solutions with a lower percentage of outages. Similarly, an increase in K increases the percentage of feasible solutions, as illustrated in Fig. 5(b). In cases where $K < D$, we cannot tolerate the reconfiguration time required by a RIS to reallocate from one robot to another. This limitation significantly restricts the usability of RISs, and unless there are numerous RISs available, the allocation problem will be infeasible in most scenarios.



(a) Percentage of outages

(b) Percentage of feasible solutions

Fig. 3: Percentage of outages and feasible solutions for the scenario of 8 RISs, where K = 10 and D = 2 time slots.



(a) Percentage of outages

(b) Percentage of feasible solutions

Fig. 4: Percentage of outages and feasible solutions for the scenario of 8 RISs and 4 robots, where K = 10 time slots.

VI. Conclusions

A proposal for ensuring reliability in RIS-assisted 6G Campus Networks is presented, particularly in scenarios with higher communication frequencies that are susceptible to LOS blockages. The paper introduced a model and optimization framework aimed at maintaining connectivity in a factory environment, taking into account the limitations of RIS technology and the practical constraints of campus networks. Furthermore, the paper discusses the control problem in RIS-assisted networks integrated into existing network architectures. The results demonstrate the tangible benefits of RIS in providing continuous connectivity while reducing outages as a cost-benefit solution. This is done while showing that it is not enough to simply have RIS in any given scenario, but appropriate optimizations have to be done to find good schedules to make full use of their potential. In terms of future research directions, there is a need to delve into the practical implementation of RIS technology in real-world scenarios to validate the proposed models and frameworks. Moreover, the scalability and dynamic reconfiguration of RIS elements to adapt to changing network conditions should be thoroughly investigated to ensure their practical applicability.

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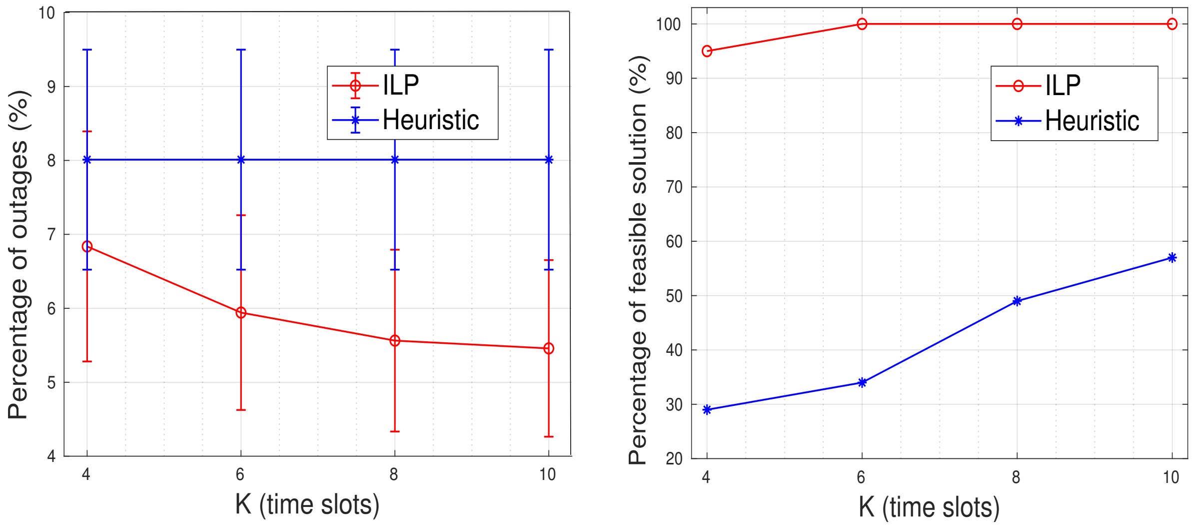

(a) Percentage of outages

(b) Percentage of feasible solutions

Fig. 5: Percentage of outages and feasible solutions for the scenario of 8 RISs and 4 robots, where D = 2 time slots.

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